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DEPARTMENT OF MECHANICAL ENGINEERING AND MECHANICS
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OLD DOMINION UNIVERSITY
NORFOLK, VIRGINIA

LARGE-AMPLITUDE MULTIMODE RESPONSE
OF CLAMPED RECTANGULAR PANELS TO
ACOUSTIC EXCITATION

By

Chuh Mei, Principal Investigator

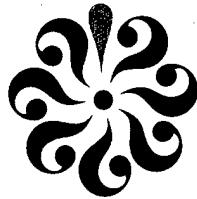
Interim Technical Report
For the period October 1, 1980 - September 30, 1981

Prepared for the
Air Force Flight Dynamics Laboratory
Wright-Patterson Air Force Base
Ohio

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Howard F. Wolfe, Program Manager
AFWAL/FIBED
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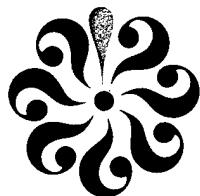
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FOREWORD

This report contains the research effort on large-amplitude multimode response of clamped rectangular panels to acoustic excitation during the period from October 1, 1980 to September 30, 1981. The work was performed at the Department of Mechanical Engineering and Mechanics, Old Dominion University, Norfolk, Virginia. The research was sponsored by the Air Force Office of Scientific Research (AFSC), Department of the Air Force, under Grant AFOSR-80-0107. The work was monitored under the supervision of Howard F. Wolfe, Technical Manager, Acoustics and Sonic Fatigue Group, Air Force Wright Aeronautical Laboratories, and Dr. Alan H. Rosenstein, AFOSR/NE, Program Manager, Directorate of Aerospace Sciences, AFSC. The author gratefully acknowledges the encouragement and assistance from Mr. Howard F. Wolfe and Dr. Donald B. Paul of AFWAL.

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LARGE AMPLITUDE MULTIMODE RESPONSE OF CLAMPED
RECTANGULAR PANELS TO ACOUSTIC EXCITATION

By

Chuh Mei

INTRODUCTION

Acoustically induced fatigue failures in structural components have resulted in unacceptable maintenance and inspection burdens associated with aircraft and missile operation. In some cases, sonic fatigue failures have resulted in major structural redesigns and aircraft modifications. Thus, accurate prediction methods are needed to determine the fatigue life of structures.

Many analytical and experimental programs to develop sonic fatigue design criteria, however, have repeatedly shown a poor comparison between measured and calculated maximum RMS stress/strain (refs. 1, 2). Deviations in excess of 100 percent are not uncommon. Large deflection nonlinearity has been identified as a major factor for the enormous discrepancy between test data and computed results (ref. 3). A test program was conducted recently to check the analytical effort for the large-amplitude, single-mode response reported in reference 3. The acoustic response tests were performed in the Wideband Acoustic Facility at Wright-Patterson Air Force Base. A comparison of the results from two panels is shown in figure 1. The prediction of random responses is much improved with the single-mode computational method, especially at high excitation levels. Test results (fig. 2) also showed that there are more than one mode responding. Multiple modes were also observed by White in experimental studies on aluminum and carbon fiber-reinforced plastics (CFRP) plates under acoustic loadings (ref. 4). White also showed that the fundamental mode responded significantly and contributed more than 80 percent of the total mean-square strain response; higher modes, up to third or fourth modes, account for 95% or more of the total mean-square strain response. In order to have an accurate prediction of the random response of a structure, multiple modes should be used in the formulation.

RESULTS COMPARISON

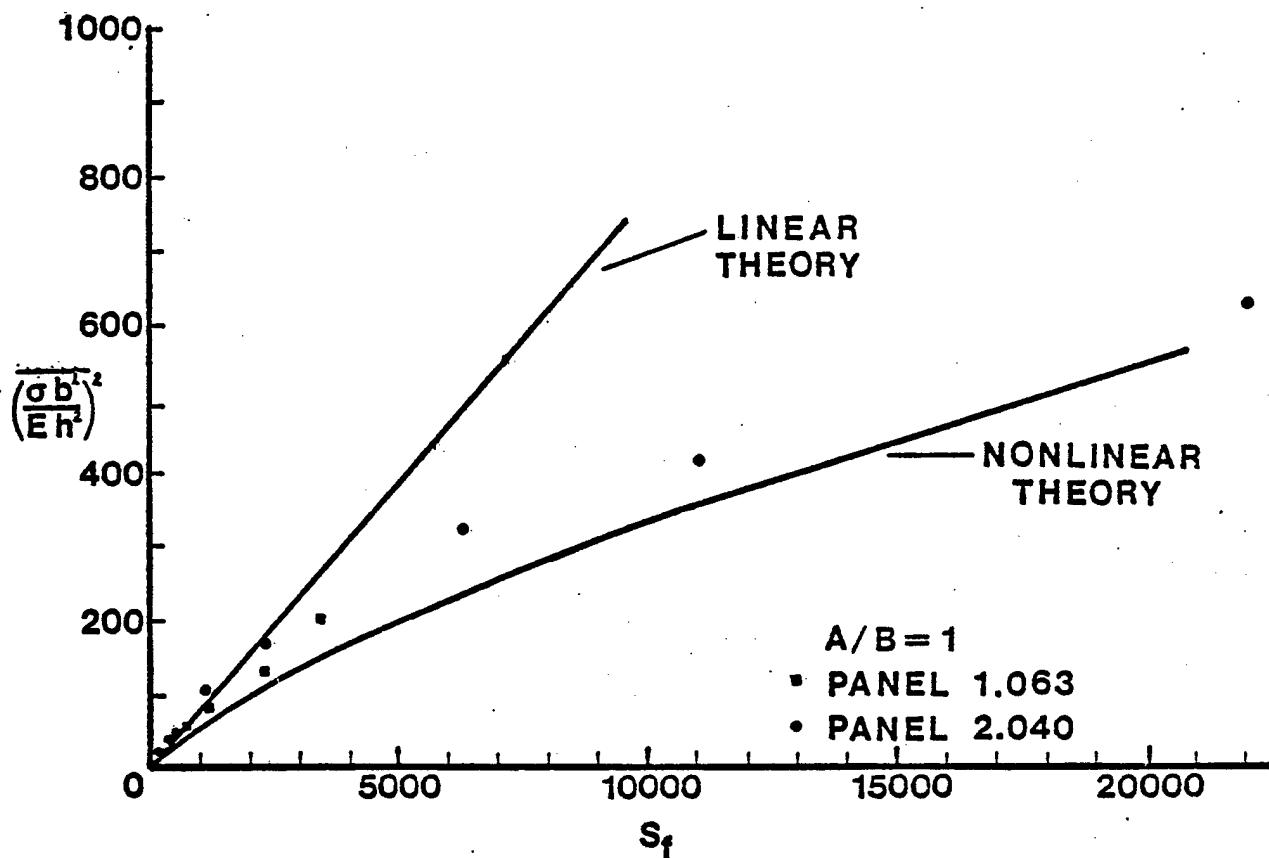


Figure 1. Comparison of analytical and experimental mean-square stresses of clamped, square, aluminum panels.

NONLINEAR RESPONSE PANEL 1.063 SG. 10
REC 14 (130 DB), 29 (142 DB), 41 (160 DB)

RMS .4816

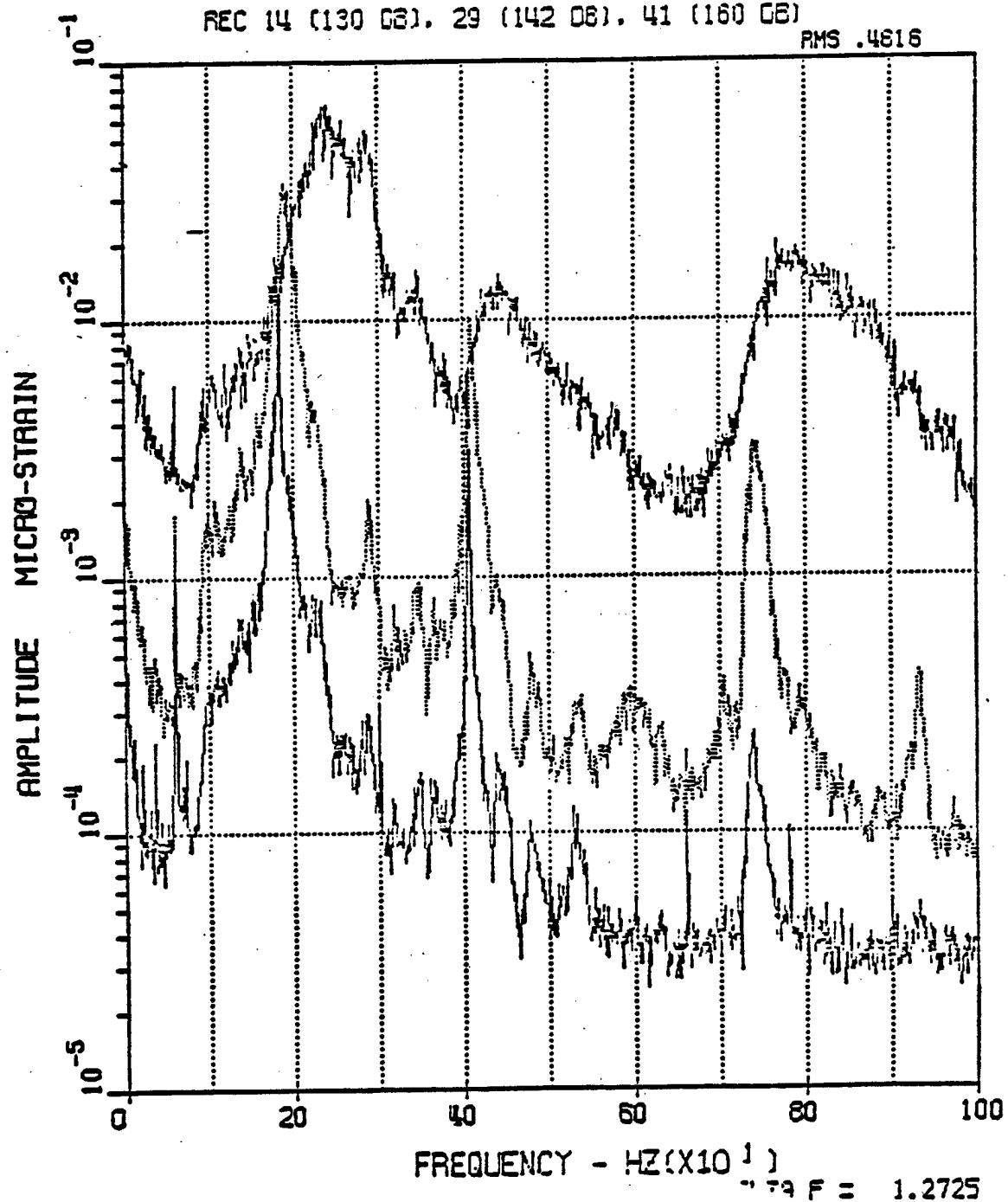


Figure 2. Strain response at three different SPL's.

NOMENCLATURE

a,b	panel length and width
C	generalized damping
D	flexural rigidity
E	Young's modulus
$f_m(x), g_n(y)$	displacement functions, eq. (21)
F	airy stress function
h	panel thickness
K	generalized stiffness
L	mathematical operator, eq. (1)
M	generalized mass
p	pressure
q	normal coordinate
r	length-to-width ratio, a/b
$S_p(\omega)$	cross-spectral density of p(t)
t	time
w	lateral deflection
W	generalized displacement
x,y	coordinates
β	vector function, eq. (16)
ζ	damping ratio, c/c_0
ϕ	normal mode
ω	linear frequency
Ω	equivalent linear or nonlinear frequency
<u>Subscripts</u>	
EL	equivalent linear
L	linear

MATHEMATICAL FORMULATION AND SOLUTION PROCEDURE

The governing equations of a rectangular, isotropic plate undergoing large-deflection motions, neglecting the effects of both inplane and rotatory inertia forces, are (refs. 5, 6)

$$\begin{aligned} L(w, F) = & D \nabla^4 w + \rho h w_{tt} + g w_t \\ & - h(F_{yy} w_{xx} + F_{xx} w_{yy} - 2 F_{xy} w_{xy}) \\ & - p(t) = 0 \end{aligned} \quad (1)$$

$$\nabla^4 F = E(w_{xy}^2 - w_{xx} w_{yy}) \quad (2)$$

where a comma denotes the partial differentiation with respect to the corresponding variable, w is the lateral deflection, F is the stress function, D is the flexural rigidity, ρ is the mass density, h is the plate thickness, p is the pressure, E is the Young's modulus, and g is the viscous damping.

The lateral deflection is assumed as

$$w(x, y, t) = h \sum_m \sum_n w_{mn}(t) f_m(x) g_n(y) \quad m, n = 1, 2, 3, \dots \quad (3)$$

where the functions $f_m(x)$ and $g_n(y)$ are so chosen that they satisfy the boundary conditions. By solving the compatibility equation, equation (2), the stress function can then be determined as

$$\begin{aligned} F = & \bar{N}_x \frac{y^2}{2} + \bar{N}_y \frac{x^2}{2} + Eh^2 \sum_i \sum_j F_{ij} N_i(x) M_j(y) \\ i, j = & 0, 1, 2, \dots \end{aligned} \quad (4)$$

A quasi-exact solution has been obtained by Paul for thermal postbuckling of a clamped, rectangular plate. The expressions for the coefficients \bar{N}_x , \bar{N}_y , and F_{ij} can be found in reference 7.

Apply the Bubnov-Galerkin method to the equation of motion in deflection, equation (1), as

$$\iint L(w, F) f_r g_s dx dy = 0 \quad r, s = 1, 2, 3, \dots \quad (5)$$

After performing the integration over the total area of the panel, a set of nonlinear, time-differential equations is obtained and can be written in matrix form as

$$[M]\ddot{\{w\}} + [C]\dot{\{w\}} + [K]_L\{w\} + \{\beta(w)\} = \{p(t)\} \quad (6)$$

where the matrices $[M]$, $[C]$, and $[K]_L$ are the generalized mass, damping, and linear stiffness matrices, respectively, and $\{\beta(w)\}$ is a vector function, cubic in the generalized displacements $\{w\}$.

An equivalent linear set of equations to equation (6) may be defined as (refs. 8-13):

$$[M]\ddot{\{w\}} + [C]\dot{\{w\}} + ([K]_L + [K]_{EL})\{w\} = \{p(t)\} \quad (7a)$$

or

$$[M]\ddot{\{w\}} + [C]\dot{\{w\}} + [K]\{w\} = \{p(t)\} \quad (7b)$$

where the elements of the equivalent linear stiffness matrix $[K]_{EL}$ can be obtained from the expression

$$(K_{EL})_{ij} = E \left[\frac{\partial \beta_j(w)}{\partial w_i} \right] \quad i, j = 1, 2, 3, \dots \quad (8)$$

where $E[\cdot]$ is an expected value operator.

To determine the mean-square generalized displacements \bar{w}_j^2 in equation (7), an iterative solution procedure is introduced. The undamped linear equation of equation (7a) is solved first. This requires the determination of the eigenvalues and eigenvectors of the undamped linear equation

$$\omega_j^2 [M] \{\phi\}_j = [K]_L \{\phi\}_j \quad (9)$$

where ω_j is the frequency of vibration and $\{\phi\}_j$ is the corresponding normal mode shape based on linear theory.

Apply a coordinate transformation, from the generalized displacements to the normal coordinates, by

$$\begin{matrix} \{w\} &= [\phi] \{q\} \\ m \times 1 & m \times n \quad n \times 1 \end{matrix} \quad (10)$$

in which each column of $[\phi]$ is a modal column of the linear system, and $\{q\}$ represents the normal coordinates. Substituting equation (10) into the damped linear equation of equation (7a) and premultiplying by the transpose of $[\phi]$, it becomes

$$[\ddot{M}] \{\ddot{q}\} + [\ddot{C}] \{\dot{q}\} + [\ddot{K}]_L \{q\} = \{P(t)\} \quad (11)$$

where $[\ddot{M}] = [\phi]^T [M] [\phi]$
 $[\ddot{K}]_L = [\phi]^T [K]_L [\phi] = [\omega^2] [\ddot{M}]$
 $[\ddot{C}] = [\phi]^T [C] [\phi] = 2[\zeta\omega] [\ddot{M}]$
 $\{P\} = [\phi]^T \{p\}$ (12)

The jth row of equation (11) is

$$\ddot{q}_j + 2\zeta_j \omega_j \dot{q}_j + \omega_j^2 q_j = \frac{p_j}{M_j} \quad (13)$$

The mean-square normal coordinate is simply

$$\bar{q_j^2} \approx \frac{\pi S_p(\omega_j)}{4 M_j^2 \zeta_j \omega_j^3} = \frac{\pi \{\phi\}_j^T [S_p(\omega_j)] \{\phi\}_j}{4 M_j^2 \zeta_j \omega_j^3} \quad (14)$$

where $[S_p]$ is the cross-spectral density matrix of the excitation $\{p(t)\}$. The covariance matrix of the linear, generalized displacements is

$$[\bar{W_i W_j}]_L = \sum_k \{\phi\}_k \frac{\pi \{\phi\}_k^T [S_p(\omega_k)] \{\phi\}_k}{4 M_k^2 \zeta_k \omega_k^3} \{\phi\}_k^T \quad (15)$$

The diagonal terms $[\bar{W_i W_j}]_L$ are the mean-square, linear, generalized displacement $\bar{w_j^2}$. This initial estimate of $\bar{w_j^2}$ can now be used to compute the equivalent linear stiffness matrix $[K]_{EL}$ through equation (8). Then equation (7) is again transformed to the normal coordinates and has the form as

$$[\ddot{M}] \{\ddot{q}\} + [\ddot{C}] \{\dot{q}\} + [\ddot{K}] \{q\} = \{P(t)\} \quad (16)$$

$$\text{where } [\ddot{K}] = [\phi]^T ([K]_L + [K]_{EL}) [\phi] = [\Omega^2] [\ddot{M}] \quad (17)$$

The jth row of equation (17) is

$$\ddot{q}_j + 2\zeta_j \omega_j \dot{q}_j + \Omega^2 q_j = \frac{P_j}{M_j} \quad (18)$$

and the displacement covariance matrix is given by

$$[\bar{W_i W_j}] = \sum_k \{\phi\}_k \frac{\pi \{\phi\}_k^T [S_p(\Omega_k)] \{\phi\}_k}{4 M_k^2 \zeta_k \Omega_k^2 \omega_k} \{\phi\}_k^T \quad (19)$$

Convergence is considered achieved whenever the difference of the RMS generalized displacements satisfies the requirement

$$\left| \frac{(\text{RMS } w_j)_{\text{iter}} - (\text{RMS } w_j)_{\text{iter-1}}}{(\text{RMS } w_j)_{\text{iter}}} \right| < 10^{-3}, \text{ for all } j \quad (20)$$

Once the RMS displacements are determined, the RMS deflection of the panel and the maximum RMS strain can be determined from equation (3) and the strain-displacement relations, respectively.

DEVELOPMENT OF GENERALIZED MATRICES
AND COMPUTER PROGRAMS

The deflection of the panel is represented by

$$w(x, y, t) = h \sum_m \sum_n W_{mn}(t) \left\{ \left[\cos \frac{(m-1)\pi x}{a} - \cos \frac{(m+1)\pi x}{a} \right] \cdot \left[\cos \frac{(n-1)\pi y}{b} - \cos \frac{(n+1)\pi y}{b} \right] \right\} \quad (21)$$

The expression w satisfies the boundary condition for clamped edges:

$$\begin{aligned} w = w_x &= 0 \quad \text{on } x = 0 \text{ and } a \\ w = w_y &= 0 \quad \text{on } y = 0 \text{ and } b \end{aligned} \quad (22)$$

The stress function can be expressed in terms of the generalized displacement W_{mn} as

$$F = \bar{N}_x \frac{y^2}{2} + \bar{N}_y \frac{x^2}{2} + Eh^2 \sum_i \sum_j F_{ij} \cos \frac{i\pi x}{a} \cos \frac{j\pi y}{b} \quad (23)$$

where the coefficient F_{ij} is given by the expression

$$F_{ij} = \frac{1}{\left(\frac{i^2}{r} + j^2 r\right)^2} \sum_m \sum_n \sum_k \sum_l B_{ijmnkl} W_{mn} W_{kl} \quad (24)$$

in which B_{ijmnkl} are integers and $r = a/b$. The coefficients \bar{N}_x and \bar{N}_y , and the integers B_{ijmnkl} are given explicitly in reference 7. The particular generalized displacements that are chosen to be nonzero in the convergence studies are shown in table 1.

Table 1. Generalized displacements for convergence studies.

<u>Generalized Displacements</u>	<u>Number of terms</u>				
	<u>1</u>	<u>4</u>	<u>6</u>	<u>10</u>	<u>15</u>
W_{11}	X	X	X	X	X
W_{13}		X	X	X	X
W_{31}		X	X	X	X
W_{33}		X	X	X	X
W_{15}			X	X	X
W_{51}			X	X	X
W_{35}				X	X
W_{53}				X	X
W_{17}				X	X
W_{71}				X	X
W_{55}					X
W_{37}					X
W_{73}					X
W_{19}					X
W_{91}					X

Utilizing the expressions for w and F , equations (21) and (23), respectively, and performing the integration of equation (5), the integral associated with the inertial force term in equation (1) has been derived as

$$\int_0^b \int_0^a \rho h w_{tt} f_r g_s dx dy = \frac{\rho h^2 ab}{4} \left(\begin{array}{l} \cdots \\ \ddot{w}_{r-2,s-2} - 2 \ddot{w}_{r-2,s} - 2 \ddot{w}_{r,s-2} \\ + 4 \ddot{w}_{r,s} - 2 \ddot{w}_{r,s+2} - 2 \ddot{w}_{r+2,s} \\ + \ddot{w}_{r-2,s+2} + \ddot{w}_{r+2,s-2} + \ddot{w}_{r+2,s+2} \end{array} \right) \quad (25)$$

The generalized mass matrix $[M]$ in equation (6) using 15 terms in the deflection function is given by:

$$[M] = \frac{\rho h^2 ab}{4} \begin{bmatrix} 4 & & & & & & & & & & & & & & & \\ -2 & 4 & & & & & & & & & & & & & & \\ -2 & 1 & 4 & & & & & & & & & & & & & \\ 1 & -2 & -2 & 4 & & & & & & & & & & & & \\ 0 & -2 & 0 & 1 & 4 & & & & & & & & & & & \\ 0 & 0 & -2 & 1 & 0 & 4 & & & & & & & & & & \\ 0 & 1 & 0 & -2 & -2 & 0 & 4 & & & & & & & & & \\ 0 & 0 & 1 & -2 & 0 & -2 & 1 & 4 & & & & & & & & \\ 0 & 0 & 0 & 0 & -2 & 0 & 1 & 0 & 4 & & & & & & & \\ 0 & 0 & 0 & 0 & 0 & -2 & 0 & 1 & 0 & 4 & & & & & & \\ 0 & 0 & 0 & 1 & 0 & 0 & -2 & -2 & 0 & 0 & 4 & & & & & \\ 0 & 0 & 0 & 0 & 1 & 0 & -2 & 0 & -2 & 0 & 1 & 4 & & & & \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & -2 & 0 & -2 & 1 & 0 & 4 & & & \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -2 & 0 & 0 & 1 & 0 & 4 & & \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -2 & 0 & 0 & 1 & 0 & 4 \end{bmatrix} \quad (26)$$

A subroutine program MASS, which generates the mass matrix, has been coded and verified. A listing of the MASS subroutine is given in the Appendix.

Similarly, the integrals associated with the linear stiffness terms in equation (1) yield

$$\int_0^b \int_0^a D \frac{\partial^4 w}{\partial x^4} f_r g_s dx dy = \frac{D h \pi^4 ab}{4a^4} \cdot \left\{ \begin{array}{l} [(r-1)^4 + (r+1)^4] [(c_1 + 1)w_{r,s} - w_{r,s-2} - w_{r,s+2}] \\ + (r-1)^4 [w_{r-2,s-2} + w_{r-2,s+2} - (c_1 + 1)w_{r-2,s}] \\ + (r+1)^4 [w_{r+2,s+2} + w_{r+2,s-2} - (c_1 + 1)w_{r+2,s}] \end{array} \right\} \quad (27)$$

$$\int_0^b \int_0^a D \frac{\partial^4 w}{\partial y^4} f_r g_s dx dy = \frac{D h \pi^4 ab}{4b^4} \cdot \left\{ \begin{array}{l} [(s-1)^4 + (s+1)^4] [(c_2 + 1)w_{r,s} - w_{r-2,s} - w_{r+2,s}] \\ + (s-1)^4 [w_{r-2,s-2} + w_{r+2,s-2} - (c_2 + 1)w_{r,s-2}] \\ + (s+1)^4 [w_{r+2,s+2} + w_{r-2,s+2} - (c_2 + 1)w_{r,s+2}] \end{array} \right\} \quad (28)$$

$$\int_0^b \int_0^a 2D \frac{\partial^4 w}{\partial x^2 \partial y^2} f_r g_s dx dy = \frac{D h \pi^4 ab}{a^2 b^2} \cdot \left\{ \begin{array}{l} (r-1)^2 (s+1)^2 [w_{r,s} - w_{r,s+2} - w_{r+2,s} + w_{r+2,s+2}] \\ + (r-1)^2 (s+1)^2 [w_{r,s} - w_{r,s+2} - w_{r-2,s} + w_{r-2,s+2}] \\ + (r+1)^2 (s-1)^2 [w_{r,s} - w_{r,s-2} - w_{r+2,s} + w_{r+2,s-2}] \\ + (r-1)^2 (s-1)^2 [w_{r,s} - w_{r,s-2} - w_{r-2,s} + w_{r-2,s-2}] \end{array} \right\} \quad (29)$$

The generalized linear stiffness matrix $[K]_L$ in equation (6) using 15 terms in the deflection function has been derived. It can be expressed as the sum of the three submatrices as

$$[K]_L = \frac{Dh\pi^4 ab}{4} \left(\frac{1}{a^4} [K]_1 + \frac{1}{b^4} [K]_2 + \frac{4}{a^2 b^2} [K]_3 \right) \quad (30)$$

The nonzero elements of the three linear stiffness submatrices are given. Since the stiffness matrix is also symmetric, only the lower left-hand side elements are given. They are

$$[K]_1 = \begin{bmatrix} W_{11} & W_{13} & W_{31} & W_{33} & W_{15} \\ 2^4(C_1+1) & & & & \\ -2^4 & 2^4(C_1+1) & & & \\ -2^4(C_1+1) & 2^4 & (2^4+4^4)(C_1+1) & & \\ 2^4 & -2^4(C_1+1) & -(2^4+4^4) & (2^4+4^4)(C_1+1) & \\ 0 & -2^4 & 0 & 2^4 & 2^4(C_1+1) \\ 0 & 0 & -4^4(C_1+1) & 4^4 & 0 \\ 0 & 2^4 & 0 & -(2^4+4^4) & -2^4(C_1+1) \\ 0 & 0 & 4^4 & -4^4(C_1+1) & 0 \\ 0 & 0 & 0 & 0 & -2^4 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\begin{bmatrix} W_{51} & W_{35} & W_{53} & W_{17} & W_{71} \\ (4^4+6^4)(C_1+1) & & & & \\ 0 & (2^4+4^4)(C_1+1) & & & \text{symmetric} \\ -(4^4+6^4) & 4^4 & (4^4+6^4)(C_1+1) & & \\ 0 & 2^4 & 0 & 2^4(C_1+1) & \\ -6^4(C_1+1) & 0 & 6^4 & 0 & (6^4+8^4)(C_1+1) \end{bmatrix} \quad (31)$$

$$[K]_2 = \begin{bmatrix} w_{11} & w_{13} & w_{31} & w_{33} & w_{15} \\ 2^4(C_2+1) & -2^4(C_2+1) & (2^4+4^4)(C_2+1) & 2^4(C_2+1) & \\ -2^4(C_2+1) & 2^4 & 2^4(C_2+1) & -2^4(C_1+1) & (2^4+4^4)(C_2+1) \\ -2^4 & 2^4 & 2^4(C_2+1) & 0 & 4^4 \\ 2^4 & -(2^4+4^4) & 0 & -2^4 & (4^4+6^4)(C_2+1) \\ 0 & -4^4(C_2+1) & 0 & 2^4 & 0 \\ 0 & 0 & -2^4 & 2^4 & \\ 0 & 4^4 & 0 & -4^4(C_2+1) & -(4^4+6^4) \\ 0 & 0 & 2^4 & - (2^4+4^4) & 0 \\ 0 & 0 & 0 & 0 & -6^4(C_2+1) \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$w_{51} \quad w_{35} \quad w_{53} \quad w_{17} \quad w_{71}$

$$\begin{bmatrix} 2^4(C_2+1) & & & & \\ 0 & (4^4+6^4)(C_2+1) & & & \text{symmetric} \\ -2^4(C_2+1) & 4^4 & (2^4+4^4)(C_2+1) & & \\ 0 & 6^4 & 0 & (6^4+8^4)(C_1+1) & \\ -2^4 & 0 & 2^4 & 0 & 2^4(C_1+1) \end{bmatrix}$$

(32)

$$[K]_3 = \begin{bmatrix} w_{11} & w_{13} & w_{31} & w_{33} & w_{15} \\ (2 \cdot 2)^2 & & & & \\ -(2 \cdot 2)^2 & (2 \cdot 4)^2 + (2 \cdot 2)^2 & & & \text{symmetric} \\ -(2 \cdot 2)^2 & (2 \cdot 2)^2 & (4 \cdot 2)^2 + (2 \cdot 2)^2 & (4 \cdot 4)^2 & \\ (2 \cdot 2)^2 & -(2 \cdot 4)^2 - (2 \cdot 2)^2 & -(4 \cdot 2)^2 - (2 \cdot 2)^2 & +2(4 \cdot 2)^2 + (2 \cdot 2)^2 & \\ 0 & -(2 \cdot 4)^2 & 0 & (2 \cdot 4)^2 & (2 \cdot 6)^2 + (2 \cdot 4)^2 \\ 0 & 0 & -(4 \cdot 2)^2 & (4 \cdot 2)^2 & 0 \\ 0 & (2 \cdot 4)^2 & 0 & -(4 \cdot 4)^2 - (2 \cdot 4)^2 & -(2 \cdot 6)^2 - (2 \cdot 4)^2 \\ 0 & 0 & (4 \cdot 2)^2 & -(4 \cdot 4)^2 - (4 \cdot 2)^2 & 0 \\ 0 & 0 & 0 & 0 & -(2 \cdot 6)^2 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\begin{bmatrix} w_{51} & w_{35} & w_{53} & w_{17} & w_{71} \\ (6 \cdot 2)^2 + (4 \cdot 2)^2 & & & & \\ 0 & (4 \cdot 6)^2 + (2 \cdot 6)^2 & & & \\ & +(4 \cdot 4)^2 + (2 \cdot 4)^2 & & & \\ -(6 \cdot 2)^2 - (4 \cdot 2)^2 & (4 \cdot 4)^2 & (6 \cdot 4)^2 + (4 \cdot 4)^2 & & \\ & & +(6 \cdot 2)^2 + (4 \cdot 2)^2 & & \\ 0 & (2 \cdot 6)^2 & 0 & (2 \cdot 8)^2 + (2 \cdot 6)^2 & \\ -(6 \cdot 2)^2 & 0 & (6 \cdot 2)^2 & 0 & (8 \cdot 2)^2 + (6 \cdot 2)^2 \\ & & & & (33) \end{bmatrix}$$

The nonzero elements of the linear stiffness matrix, $k_L(i,j)$ for $i,j \geq 11$, are

$$\begin{aligned} k_L(11,4) &= k_L(12,11) = 4^4 \\ k_L(12,5) &= k_L(14,12) = 2^4 \\ k_L(13,6) &= k_L(13,11) = 6^4 \\ k_L(11,7) &= -4^4 (C_1 + 1) \\ k_L(12,7) &= -(2^4 + 4^4) \\ k_L(11,8) &= -(4^4 + 6^4) \end{aligned} \tag{34}$$

(cont'd)

$$\begin{aligned}
k_1(13,8) &= -6^4 (C_1 + 1) \\
k_1(12,9) &= -2^4 (C_1 + 1) \\
k_1(14,9) &= -2^4 \\
k_1(13,10) &= -(6^4 + 8^4) \\
k_1(15,10) &= -8^4 (C_1 + 1) \\
k_1(11,11) &= (4^4 + 6^4)(C_1 + 1) \\
k_1(12,12) &= (2^4 + 4^4)(C_1 + 1) \\
k_1(13,13) &= (6^4 + 8^4)(C_1 + 1) \\
k_1(15,13) &= 8^4 \\
k_1(14,14) &= 2^4 (C_1 + 1) \\
k_1(15,15) &= (8^4 + 10^4)(C_1 + 1) \\
k_2(11,4) &= k_2(13,11) = 4^4 \\
k_2(12,5) &= k_2(12,11) = 6^4 \\
k_2(13,6) &= k_2(15,13) = 2^4 \\
k_2(11,7) &= -(4^4 + 6^4) \\
k_2(12,7) &= -6^4 (C_2 + 1) \\
k_2(11,8) &= -4^4 (C_2 + 1) \\
k_2(13,8) &= -(2^4 + 4^4) \\
k_2(12,9) &= -(6^4 + 8^4) \\
k_2(14,9) &= -8^4 (C_2 + 1) \\
k_2(13,10) &= -2^4 (C_2 + 1) \\
k_2(15,10) &= -2^4 \\
k_2(11,11) &= (4 + 6)(C_2 + 1) \\
k_2(12,12) &= (6^4 + 8^4)(C_2 + 1) \\
k_2(14,12) &= 8^4 \\
k_2(13,13) &= (2^4 + 4^4)(C_2 + 1) \\
k_2(14,14) &= (8^4 + 10^4)(C_2 + 1) \\
k_2(15,15) &= 2^4 (C_2 + 1) \\
k_3(11,4) &= (4 \cdot 4)^2 \\
k_3(12,5) &= k_3(13,6) = (2 \cdot 6)^2 \\
k_3(11,7) &= k_3(11,8) = -(4 \cdot 4)^2 - (4 \cdot 6)^2 \\
k_3(12,7) &= k_3(13,8) = -(2 \cdot 6)^2 - (4 \cdot 6)^2 \\
k_3(12,9) &= k_3(13,10) = -(2 \cdot 6)^2 - (2 \cdot 8)^2 \\
k_3(14,9) &= k_3(15,10) = -(2 \cdot 8)^2 \\
k_3(11,11) &= (6 \cdot 6)^2 + 2(6 \cdot 4)^2 + (4 \cdot 4)^2 && (34) \\
k_3(12,11) &= k_3(13,11) = (4 \cdot 6)^2 && (\text{cont'd})
\end{aligned}$$

$$k_3(12,12) = k_3(13,13) = (4 \cdot 8)^2 + (2 \cdot 8)^2 + (4 \cdot 6)^2 + (2 \cdot 6)^2 \quad (34)$$

$$k_3(14,14) = k_3(15,15) = (2 \cdot 8)^2 + (2 \cdot 10)^2$$

(concl'd)

where

$$C_1 = \begin{cases} 2 & \text{for } s = 1 \\ 1 & \text{for } s \neq 1 \end{cases}$$

$$C_2 = \begin{cases} 2 & \text{for } r = 1 \\ 1 & \text{for } r \neq 1 \end{cases} \quad (35)$$

A subroutine program LSTF which generates the linear stiffness matrix has been coded and verified. A listing of the LSTF subroutine is presented in the Appendix.

Derivation of the generalized equivalent linear stiffness matrix $[K]_{EL}$ in equation (7a) has been initiated. It is in good progress. Continuing research effort will be devoted to the following tasks:

- (1) Completion of the derivation of equivalent linear stiffness;
- (2) Application of eigen solution and coordinate transformation;
- (3) Determination of mean-square linear generalized displacement;
- (4) Implementation of the iterative process;
- (5) Derivation of strains computation;
- (6) Coding, debugging, and verifying the complete computer program;
- (7) Convergence studies; and
- (8) Generation of design charts.?

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APPENDIX

LISTINGS OF THE MASS AND LSTF SUBROUTINES

```

1 00001      SUBROUTINE MASS(AL,BL,H,RHO,SM,NTERM)
2 00002      DIMENSION SM(NTERM,NTERM)
3 00003      C
4 00004      C - THIS SUBROUTINE GENERATES THE SYSTEM MASS MATRIX OF THE PANEL USING
5 00005      C (NTERM) TERMS IN THE DEFLECTION FUNCTION
6 00006      C AL= PANEL LENGTH.
7 00007      C BL=PANEL WIDTH
8 00008      C H=PANEL THICKNESS
9 00009      C RHO=MASS DENSITY
10 00010      C SM(NTERM,NTERM)=SYSTEM OR GENERALIZED MASS MATRIX
11 00011      C NTERM=1, 4, 6, 10, OR 15
12 00012      C
13 00013      COEF=0.25*RHO*H*H*AL*BL
14 00014      C INITIALIZED THE MASS MATRIX
15 00015      DO 10 I=1,NTERM
16 00016      DO 10 J=1,NTERM
17 00017      SM(I,J)=0.0
18 00018      10 CONTINUE
19 00019      SM(I,I)=4.0*COEF
20 00020      IF (NTERM .EQ. 1) GO TO 20
21 00021      C
22 00022      SM(1,2)=-2.0*COEF
23 00023      SM(1,3)=-2.0*COEF
24 00024      SM(1,4)=COEF
25 00025      SM(2,2)=4.0*COEF
26 00026      SM(2,3)=COEF
27 00027      SM(2,4)=-2.0*COEF
28 00028      SM(3,3)=4.0*COEF
29 00029      SM(3,4)=-2.0*COEF
30 00030      SM(4,4)=4.0*COEF
31 00031      IF (NTERM .EQ. 4) GO TO 20
32 00032      C
33 00033      SM(2,5)=-2.0*COEF
34 00034      SM(3,6)=-2.0*COEF
35 00035      SM(4,5)=COEF
36 00036      SM(4,6)=COEF
37 00037      SM(5,5)=4.0*COEF
38 00038      SM(6,6)=4.0*COEF
39 00039      IF (NTERM .EQ. 6) GO TO 20
40 00040      C
41 00041      SM(2,7)=COEF
42 00042      SM(3,8)=COEF
43 00043      SM(4,7)=-2.0*COEF
44 00044      SM(4,8)=-2.0*COEF
45 00045      SM(5,7)=-2.0*COEF
46 00046      SM(5,9)=-2.0*COEF
47 00047      SM(6,8)=-2.0*COEF
48 00048      SM(6,10)=-2.0*COEF
49 00049      SM(7,7)=4.0*COEF
50 00050      SM(7,8)=COEF
51 00051      SM(7,9)=COEF
52 00052      SM(8,8)=4.0*COEF
53 00053      SM(8,10)=COEF
54 00054      SM(9,9)=4.0*COEF
55 00055      SM(10,10)=4.0*COEF
56 00056      IF (NTERM .EQ. 10) GO TO 20
57

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00057 C
2 00058      SM(4,11)=COEF
3 00059      SM(5,12)=COEF
4 00060      SM(6,13)=COEF
5 00061      SM(7,11)=-2.0*COEF
6 00062      SM(7,12)=-2.0*COEF
7 00063      SM(8,11)=-2.0*COEF
8 00064      SM(8,13)=-2.0*COEF
9 00065      SM(9,12)=-2.0*COEF
10 00066      SM(9,14)=-2.0*COEF
11 00067      SM(10,13)=-2.0*COEF
12 00068      SM(10,15)=-2.0*COEF
13 00069      SM(11,11)=4.0*COEF
14 00070      SM(11,12)=COEF
15 00071      SM(11,13)=COEF
16 00072      SM(12,12)=4.0*COEF
17 00073      SM(12,14)=COEF
18 00074      SM(13,13)=4.0*COEF
19 00075      SM(13,15)=COEF
20 00076      SM(14,14)=4.0*COEF
21 00077      SM(15,15)=4.0*COEF
22 00078    20 CONTINUE
23 00079      DO 30 J=1,NTERM
24 00080      DO 30 I=J,NTERM
25 00081      SM(I,J)=SM(J,I)
26 00082    30 CONTINUE
27 00083      RETURN
28 00084      END,
29
30
31 SUBPROGRAMS CALLED
32
33
34 SCALARS AND ARRAYS [ *** NO EXPLICIT DEFINITION • #3" NOT REFERENCED ]
35
36
37 *NTERM 1      *COEF 2      *H 3      *BL 4      SM 5
38 *J 6      .S6003 7      .S6002 10     .S6001 11     .S6000 12
39 *RHO 13      *AL 14      .I6002 15     .I6001 16     *I 17
40 .I6000 20
41
42 TEMPORARIES
43
44 .A0016 21
45
46 MASS [ NO ERRORS DETECTED ]
47
48
49
50
51
52
53
54
55
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57

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1 00001      SUBROUTINE LSTF(AL,BL,H,D,PI,SK,NTERM)
2 00002      DIMENSION SK(NTERM,NTERM)
3 00003      C
4 00004      C THIS SUBROUTINE GENERATES THE SYSTEM LINEAR STIFFNESS MATRIX
5 00005      C USING (NTERM) TERMS IN THE DEFLECTION FUNCTION FOR THE PANEL
6 00006      C AL=PANEL LENGTH
7 00007      C BL=PANEL WIDTH
8 00008      C H=PANEL THICKNESS
9 00009      C D=E*H**3/((12.0*(1-V**2))=BENDING RIGIDITY
10 00010      C V=POISSON'S RATIO
11 00011      C SK(NTERM,NTERM)=SYSTEM OR GENERALIZED STIFFNESS MATRIX
12 00012      C NTERM=1, 4, 6, 10, OR 15
13 00013      C
14 00014      PI4=PI*PI*PI*PI
15 00015      COEF=4.0*D*H*PI4*AL*BL
16 00016      A4=1.0/(AL*AL*AL*AL)
17 00017      B4=1.0/(BL*BL*BL*BL)
18 00018      AB2=4.0/(AL*AL*BL*BL)
19 00019      C C1=C1 FOR S<>1,C1=CC1 FOR S=1
20 00020      C C2=C2 FOR R<>1,C2=CC2 FOR R=1
21 00021      C1=1.0
22 00022      C2=1.0
23 00023      CC1=2.0
24 00024      CC2=2.0
25 00025      C INITIALIZED THE STIFFNESS MATRIX
26 00026      DO 10 I=1,NTERM
27 00027      DO 10 J=1,NTERM
28 00028      SK(I,J)=0.0
29 00029      10 CONTINUE
30 00030      SK(1,1)=((CC1+1.0)*A4+(CC2+1.0)*B4+AB2)*COEF
31 00031      IF(NTERM .EQ. 1) GO TO 20
32 00032      C
33 00033      SK(1,2)=-(CC2+1.0)*B4+A4+AB2)*COEF
34 00034      SK(1,3)=-(CC1+1.0)*A4+B4+AB2)*COEF
35 00035      SK(1,4)=(A4+B4+AB2)*COEF
36 00036      SK(2,2)=(17.0*(CC2+1.0)*B4+(C1+1.0)*A4+5.0*AB2)*COEF
37 00037      SK(2,3)=(A4+B4+AB2)*COEF
38 00038      SK(2,4)=-(C1+1.0)*A4+17.0*B4+5.0*AB2)*COEF
39 00039      SK(2,5)=(17.0*(CC1+1.0)*A4+(C2+1.0)*B4+5.0*AB2)*COEF
40 00040      SK(3,4)=-(C2+1.0)*B4+17.0*A4+5.0*AB2)*COEF
41 00041      SK(4,4)=(17.0*(C1+1.0)*A4+17.0*(C2+1.0)*B4+25.0*AB2)*COEF
42 00042      IF(NTERM .EQ. 4) GO TO 20
43 00043      C
44 00044      SK(2,5)=-(16.0*(CC2+1.0)*B4+A4+4.0*AB2)*COEF
45 00045      SK(3,6)=-(16.0*(CC1+1.0)*A4+B4+4.0*AB2)*COEF
46 00046      SK(4,5)=(A4+16.0*B4+4.0*AB2)*COEF
47 00047      SK(4,6)=(16.0*A4+B4+4.0*AB2)*COEF
48 00048      SK(5,5)=((C1+1.0)*A4+97.0*(CC2+1.0)*B4+13.0*AB2)*COEF
49 00049      SK(6,6)=(97.0*(CC1+1.0)*A4+(C2+1.0)*B4+13.0*AB2)*COEF
50 00050      IF(NTERM .EQ. 6) GO TO 20
51 00051      C
52 00052      SK(2,7)=(A4+16.0*B4+4.0*AB2)*COEF
53 00053      SK(3,8)=(16.0*A4+B4+4.0*AB2)*COEF
54 00054      SK(4,7)=-(17.0*A4+16.0*(C2+1.0)*B4+20.0*AB2)*COEF
55 00055      SK(4,8)=-(16.0*(C1+1.0)*A4+17.0*B4+20.0*AB2)*COEF
56 00056      SK(5,7)=-(C1+1.0)*A4+97.0*B4+13.0*AB2)*COEF
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1 00057      SK(5,9)=-(A4+81.0*(CC2+1.0)*B4+9.0*AB2)*COEF
2 00058      SK(6,8)=-(97.0*A4+(C2+1.0)*B4+13.0*AB2)*COEF
3 00059      SK(6,17)=-(81.0*(CC1+1.0)*A4+B4+9.0*AB2)*COEF
4 00060      SK(7,7)=(17.0*(C1+1.0)*A4+97.0*(C2+1.0)*B4+65.0*AB2)*COEF
5 00061      SK(7,8)=16.0*(A4+B4+AB2)*COEF
6 00062      SK(7,9)=(A4+81.0*B4+9.0*AB2)*COEF
7 00063      SK(8,8)=(97.0*(C1+1.0)*A4+17.0*(C2+1.0)*B4+65.0*AB2)*COEF
8 00064      SK(8,10)=(81.0*A4+B4+9.0*AB2)*COEF
9 00065      SK(9,9)=((C1+1.0)*A4+337.0*(CC2+1.0)*B4+25.0*AB2)*COEF
10 00066     SK(10,10)=(337.0*(CC1+1.0)*A4+(C2+1.0)*B4+25.0*AB2)*COEF
11 00067     IF(NTERM .EQ. 10) GO TO 20
12 00068     C
13 00069     SK(1,11)=16.0*(A4+B4+AB2)*COEF
14 00070     SK(5,12)=(A4+81.0*B4+9.0*AB2)*COEF
15 00071     SK(5,13)=(A4+81.0*A4+9.0*AB2)*COEF
16 00072     SK(7,11)=-(16.0*(C1+1.0)*A4+97.0*B4+52.0*AB2)*COEF
17 00073     SK(7,12)=-(17.0*A4+81.0*(C2+1.0)*B4+45.0*AB2)*COEF
18 00074     SK(8,11)=-(97.0*A4+16.0*(C2+1.0)*B4+52.0*AB2)*COEF
19 00075     SK(8,13)=-(81.0*(C1+1.0)*A4+17.0*B4+45.0*AB2)*COEF
20 00076     SK(9,12)=-(C1+1.0)*A4+337.0*B4+25.0*AB2)*COEF
21 00077     SK(9,14)=-(A4+256.0*(CC2+1.0)*B4+16.0*AB2)*COEF
22 00078     SK(10,13)=-(337.0*A4+(C2+1.0)*B4+25.0*AB2)*COEF
23 00079     SK(10,15)=-(256.0*(CC1+1.0)*A4+B4+16.0*AB2)*COEF
24 00080     SK(11,11)=(97.0*(C1+1.0)*A4+97.0*(C2+1.0)*B4+169.0*AB2)*COEF
25 00081     SK(11,12)=(16.0*A4+81.0*B4+36.0*AB2)*COEF
26 00082     SK(11,13)=(81.0*A4+16.0*B4+36.0*AB2)*COEF
27 00083     SK(12,12)=(17.0*(C1+1.0)*A4+337.0*(C2+1.0)*B4+125.0*AB2)*COEF
28 00084     SK(12,14)=(A4+256.0*B4+16.0*AB2)*COEF
29 00085     SK(13,13)=(337.0*(C1+1.0)*A4+17.0*(C2+1.0)*B4+125.0*AB2)*COEF
30 00086     SK(13,15)=(B4+256.0*A4+16.0*AB2)*COEF
31 00087     SK(14,14)=((C1+1.0)*A4+881.0*(CC2+1.0)*B4+41.0*AB2)*COEF
32 00088     SK(15,15)=((C2+1.0)*B4+881.0*(CC1+1.0)*A4+41.0*AB2)*COEF
33 00089     20  CONTINUE
34 00090     DO 30 J=1,NTERM
35 00091     DO 30 I=J,NTERM
36 00092     SK(I,J)=SK(J,I)
37 00093     30  CONTINUE
38 00094     RETURN
39 00095     END
40
41
42 SUBPROGRAMS CALLED
43
44
45
46 SCALARS AND ARRAYS [ *** NO EXPLICIT DEFINITION - % NOT REFERENCED ]
47
48 *A4      1      *NTERM   2      *COEF    3      *PI     4      *H      5
49 *CC1      6      *BL     7      *J     10      *D     11      *AB2    12
50 *S0003 13      *S0002 14      *S0001 15      *S0000 16      *B4     17
51 *CC2      20      *C2     21      *PI4    22      *AL     23      *SK     24
52 ,I0002 25      .I0001 26      *I     27      .I0000 30      *C1     31
53
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55
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